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TECHNICAL REPORT
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DEVELOPMENT OF A MANUFACTURABLE BLUE ELECTROLUMINESCENT (EL) PHOSPHOR PROCESS FOR THE PRODUCTION OF WHITE MONOCHROME THIN FILM ELECTROLUMINESCENT (TFEL) AND FULL COLOR ACTIVE MATRIX ELECTROLUMINESCENT (AMEL) DISPLAYS

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14. ABSTRACT
This report documents the effort for scaling up and integrating the strontium sulfide doped with copper (SrS:Cu) vapor deposition process developed at Georgia Tech Research Institute (GTRI) for the manufacturing of color active matrix electroluminescent (AMEL) displays at Planar Systems. The development consisted of three major tasks: 1) investigate processing issues such as substrate type/morphology and sulfur annealing and their effect on the reliability and luminance performance of SrS:Cu blue phosphor. 2) install a new process infrastructure to perform post deposition processes, e.g., photolithography and etching of 1.4 inch-square substrates for the fabrication of AMEL displays, 3) investigate and identify tools for manufacturing SrS:Cu-based full color AMEL with high yield. Each of these tasks will be described with details in this report. Several SrS:Cu- based white monochrome AMEL displays were produced at the end of this program and they exhibited a factor of six increase in blue luminance (through color filter) over strontium sulfide doped with cerium (SrS:Ce) -based white monochrome displays currentlyin production. All these efforts form the basis for producing cost effective and high performance full color AMEL displays for military and civilian applications.

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BLUE PHOSPHORS; AMEL(ACTIVE MATRIX ELECTROLUMINESCENT); VAPOR DEPOSITION; MILITARY APPLICATIONS; MONOCHROME DISPLAYS; PIXELS; COMPUTER DISPLAYS

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PREFACE

This report describes a joint effort between Georgia Tech Research Institute (GTRI) and Planar Systems to develop a manufacturable strontium sulfide doped with copper (SrS:Cu) blue phosphor deposition process for next generation full color AMEL displays for military and civilian applications. The project was completed during the period April 2000 to April 2002, contract number C-DAAD16-00-C-9235, under the direction of US Army Soldier Systems Center, Natick, MA.

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SUMMARY

The focus of this effort has been to scale up and integrate the strontium sulfide doped with copper (SrS:Cu) vapor deposition process developed at Georgia Tech Research Institute (GTRI) for the manufacturing of color active matrix electroluminescent (AMEL) displays at Planar for military and civilian applications.

Processing issues such as substrate effect and sulfur annealing were carefully investigated. A clear understanding of these issues contributes to the optimization of process conditions for achieving high reliability and luminance performance on real integrated circuit (IC) wafers.

A new process infrastructure was established to perform post deposition photolithography on 1.4-inch-square substrates for the fabrication of AMEL displays. The circuit yield was steadily improved and several functional and reliable displays were produced toward the end of the program. These SrS:Cu-based white monochrome AMEL displays performed as expected and exhibited a factor of six increase in blue luminance (through color filter) over SrS:Ce-based white monochrome displays.

In the end, the objective set for this program, i.e., to develop a manufacturable SrS:Cu blue phosphor process for the production of white monochrome and full color AMEL displays, has been met by the demonstration of functional SrS:Cu-based white monochrome QVGA displays with blue where white luminance performance greatly exceeds the SrS:Ce-based displays currently in production. In addition, tools for manufacturing SrS:Cu-based full color AMEL with high yield were also investigated and identified. All these efforts form the basis for producing cost effective and high performance full color AMEL displays for military and civilian applications which is the ultimate goal of this government program.

1. Introduction

The objective of this program is to scale up and integrate the SrS:Cu e-beam evaporation process developed at GTRI for the manufacturing of color AMEL and monochrome white thin film electroluminescent (TFEL) display for military and civilian applications. However, in the first two quarters of the program, GTRI has experienced severe difficulty in bringing up the performance of SrS:Cu e-beam evaporation process to meet the program goal. At the same time, Planar decided to focus all future blue and white phosphor development on color AMEL applications. This led to the decision for GTRI to refocus on the implementation of their vapor phase deposition (VPD) SrS:Cu process for color AMEL fabrication. VPD SrS:Cu deposition on Si substrates using their molecular beam epitaxy (MBE) tool was a new challenge for GTRI. A new set of fixtures for handling Si substrates in MBE tool had to be built. In addition, the process parameters had to be developed for Si substrates since earlier results were based on glass substrates and VPD process is known to be sensitive to the thermal properties of the substrates. Furthermore, since GTRI's MBE tool can only handle 1.4 inch square substrates, Planar had to develop a process infrastructure to handle this odd size of substrates for building AMEL displays. A number of expected and unexpected challenging issues were encountered during the course of the program. Fortunately, after six quarters of hard work, we can now report that we have met the revised program goal by demonstrating fully functional and reliable white monochrome AMEL displays with color luminance performance greatly exceeds the SrS:Ce-based AMEL displays that are currently in production.

2. SrS:Cu Deposition

2.1 Growth System

A modified EPI Modular Gen II system with a Balzers TMU1000 turbo-molecular pump, a custom sample loadlock chamber and five-sample trolley system was employed for this study. Strontium and copper were thermally evaporated from pyrolytic boron nitride (pBN) crucibles. The sulfur was supplied using either t-butyl mercaptan (t-BuSH) or H_2S and delivered through a MKS 1159 mass flow controller. A gas sulfur source was used since it was easier to control the flow rate and to maintain the system vacuum than with a solid sulfur source. Although, samples grown using t-BuSH showed a higher EL brightness. The cost of high purity t-BuSH is much more expensive. H_2S was used for most of the studies for the purpose of cutting the production costs. Cu and Sr metals were thermally evaporated during the growth. To ensure purity of the films, SrS:Cu was grown under high S to Sr ratios. The Sr and Cu flux were measured by standard ion gauge to achieve proper growth rate and doping concentration. The Cu flux was fixed at 2×10^{-8} torr and the Sr flux was adjusted by changing the effusion cell temperature for the growth studies. The surface morphology of the films was studied by secondary electron microscopy (SEM) and atomic force microscopy (AFM). Photoluminescence spectroscopy (PL) was used to measure the spectral distribution, intensity, and decay time from which the film optical quality was assessed. The PL measurements were performed using a Spectra-Physics BeamLok 2085 Argon Ion laser with 275nm single line optics.

VPD grown SrS:Cu on glass substrate showed a comparable EL brightness to those processed by sputtering with high temperature RTA. It also had an extremely steep turn on with excellent aging behavior as shown in Figure 1. These results indicated that VPD process can produce extremely high quality SrS:Cu layers even without high temperature anneal.

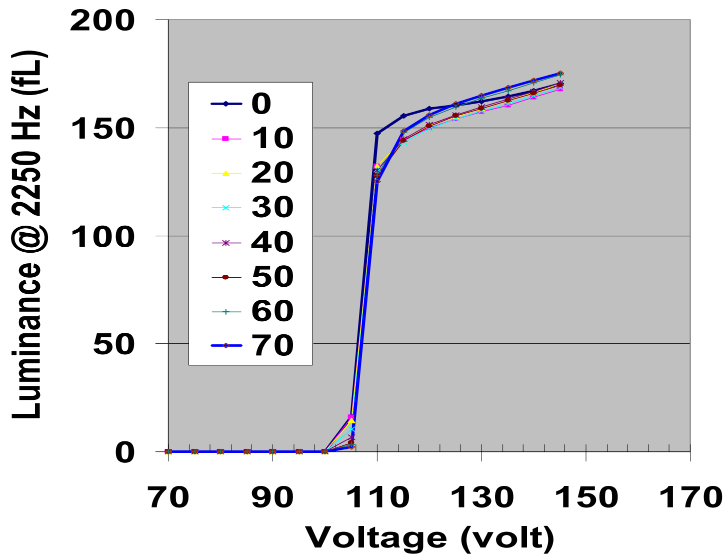

Figure 1. Aging Characteristics of SrS:Cu Grown by VPD

However, it is expected that VPD growth of SrS:Cu on AMEL wafer will be more difficult due to the large thermal expansion and the much more complicated substrate surface morphology which will greatly alter the heat distribution as well as the path of Cu diffusion during the growth and anneal phase. Therefore, the process was investigated with three kinds of Si substrates in stages, i.e. bare Si substrates with simple metal stripes (stripe wafers), Si wafers coated with patterned lower electrode (patterned test wafers), and real AMEL (IC wafers), so that a smooth transition and understanding to the impact of substrate surface condition on the SrS:Cu film quality and EL performance could be obtained. Both stripe wafer and patterned test wafers have smooth surface with single metal layer while the IC wafers have a rough surface and multiple layers of patterned metal and dielectrics underneath the surface. There are significant variations of thermal properties from location to location across IC wafers, sometimes within a few micrometers in distance.

A mechanical substrate mounting was made as shown in Figure 2. The mounting mechanism was carefully designed to minimize any film cracking or peeling caused by mechanical tension to the substrate. The substrate temperature control thermocouple was also modified to eliminate the spring loading tension onto the back of the substrate.

Figure 2. Mechanical Mounting for AMEL Substrate

2.2 Substrate Effects on Growth Conditions

Shown in Figure 3 is the PL emissions from SrS:Cu grown onto a bare Si and onto a simple metal stripe wafers. Although the growth condition of both samples was identical, the large difference in the PL intensity indicated that the surface condition had a large impact on the film quality. The growth condition for different kind of substrates, therefore, had to be studied and fine tuned to achieve good EL performance. The study of the growth conditions on these different substrates can provide valuable information for the understanding of nucleation process on the substrate so that a better process can be designed based on this knowledge.

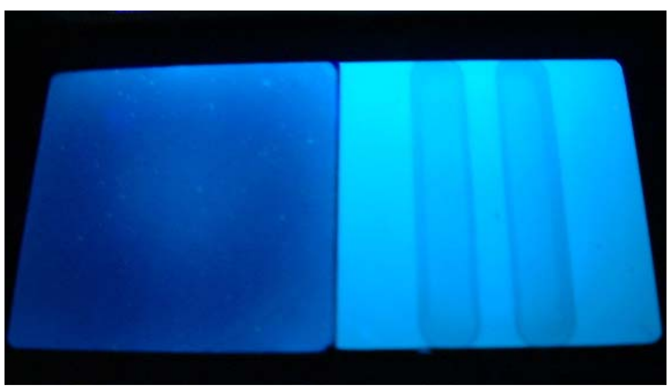

Figure 3. SrS:Cu PL Emission from Bare Si (left), and Metal Stripe Si Substrates (right)

The impact of the substrate surface conditions on the grain growth of SrS:Cu can also be seen from AFM studies of SrS:Cu films n patterned test and IC wafers, as shown in Figure 4. The grain size on the patterned test wafers is much larger than on the IC wafers. We also found that the grain size on simple metal striped wafer was even larger when same growth condition was used to grow SrS:Cu. It appears that the roughest substrate surface results in the smallest grain size and consequently the worst EL performance. Earlier study showed that the grain growth occurred during the sulfur annealing step. The reaction between sulfur and copper ionized the copper atom accumulated at the grain boundary and formed Cu_2S. The Cu_2S then diffuses back into the grain. This diffusion effectively reduces the energy barrier for grain boundary movement and stimulates a large grain growth in a chain reaction fashion. On a rough surface, such as the one on IC wafers, the edge of the pixels appears to constrain the grain boundary movement. In addition, the multiple layers of patterned metal and dielectric on IC wafers can cause the surface heat to be distributed unevenly. This in return reduces the heat energy available to the reaction and hence the varying grain sizes observed on IC wafers.

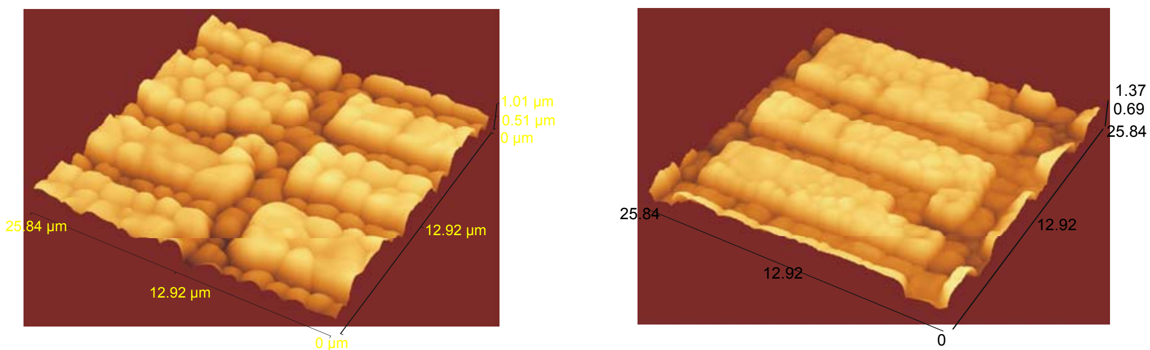

Figure 4. AFM Studies of Grain Size of SrS:Cu Grown on Patterned Test Wafers (left) and IC Wafer (right)

It is important to point out that the growth condition of SrS:Cu shown in Figure 4 was optimized for the grain size. In general, the grain size achieved on regular samples is much smaller than those shown in the figure. At optimized growth condition, the grain size can be as large as 2 to 3 µm on a smooth Si substrate but less than 0.5µm on AMEL substrate.

A systematic investigation of SrS:Cu growth was carried out using patterned test wafers to gain better understanding of SrS:Cu growth mechanism on pixelated surface so that the growth conditions on real AMEL substrates can be achieved with minimum cost and time. It was found that in general the growth temperature on textured surface should be lowered to reduce the Cu migration to the corners at the pixel area. This is important for device reliability since too much residual copper can cause devices to burn out below or near threshold voltage. Furthermore, EL brightness is very sensitive to the Cu concentration on the pixelated substrates. As shown in Figure 5, a factor of three changes was observed (sample 84 vs. 65) for only about 2-3% percent change in the Cu concentration (Cu concentration variation was achieved by change in Sr flux).

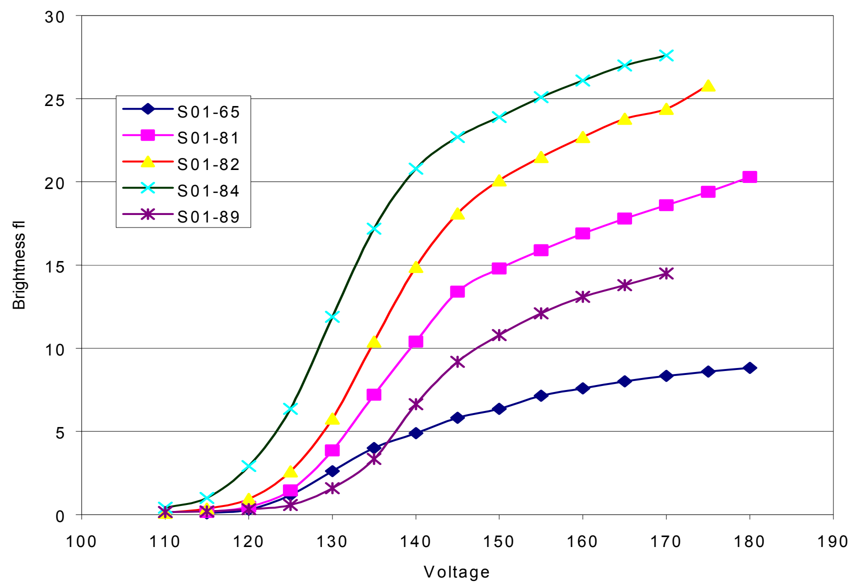

Figure 5. Variation of Blue Filtered L-V Characteristics of SrS:Cu on Patterned Test Wafers Caused by Cu Concentration Change When Sr Flux Was Varied (2.25khz, 100% duty)

Reproducibility and control are the key factors enabling cost effective mass production of SrS:Cu-based AMELs. Although the MBE tool can produce high quality SrS:Cu which can fulfill the AMEL requirement, the reproducibility is not quite good enough for mass production due to both the very narrow process window of SrS:Cu and intrinsic ion gauge control uncertainty.

Earlier studies have shown that a high breakdown strength in SrS:Cu is obtained when the copper doping is at an optimum for luminance performance. As shown in Figures 6 and 7, both grain size and photoluminescence intensity increase drastically with copper concentration and reached an optimum at around 0.2 atomic %. At higher copper concentration, the SrS:Cu devices tend to burn out due to the formation of copper sulfide. At lower concentration, the devices also tend to burn out easily due to poor crystalline structure (as evidenced by the small grain size). It is clear from the figures that the optimum range of copper concentration is very narrow, the process window is rather limited. It is very difficult to develop and maintain consistent process conditions for growing SrS:Cu. Besides, the process conditions have to be optimized for each specific substrate type due to the variation of thermal properties between substrate types. Because of the narrow optimum operation range, a reproducible process requires a precise control of both strontium flux and substrate temperature within 1% accuracy since these two parameters determine the growth rate and hence the doping concentration. However, conventional MBE system control technique is not enough to ensure this high control accuracy of SrS:Cu growth. Strontium has a high vapor pressure (10^{-4} Torr at 394°C) which requires a constant monitoring and correction of Sr flux to ensure the stable growth rate and hence Cu concentration. It is almost impossible to achieve precision control of Sr flux using conventional ion gauge technique. During the growth, the camber pressure is in the range of middle 10^{-6} Torr, too high for the ion gauge to read the Sr flux (10^{-7} Torr). It is only possible to read Sr flux at the beginning of the run. In addition, the Sr flux reading drifts gradually due to the reaction between Sr and the ion gauge filament. Ion gauge also suffers from its inherent limitations of material selectivity and/or sensitivity. It has an uncertainty of 10 to 15%. These drawbacks make it is impractical to use ion gauge as SrS:Cu production process flux control tool.

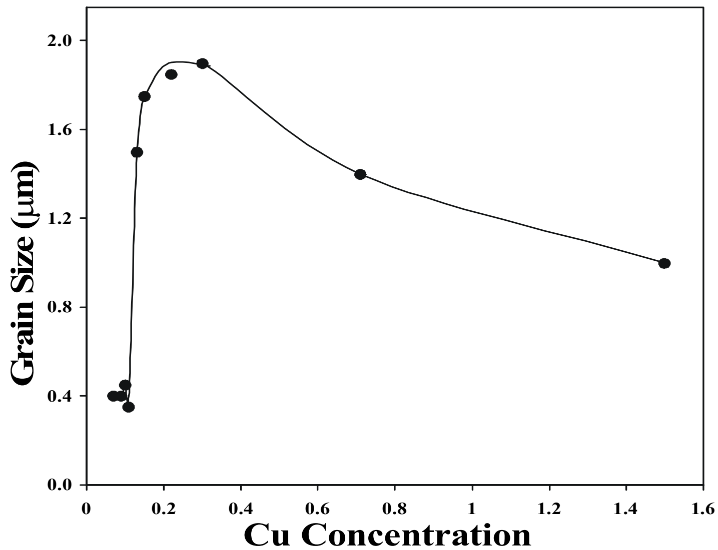

Figure 6. SrS:Cu Grain Size as a Function of Cu Concentration

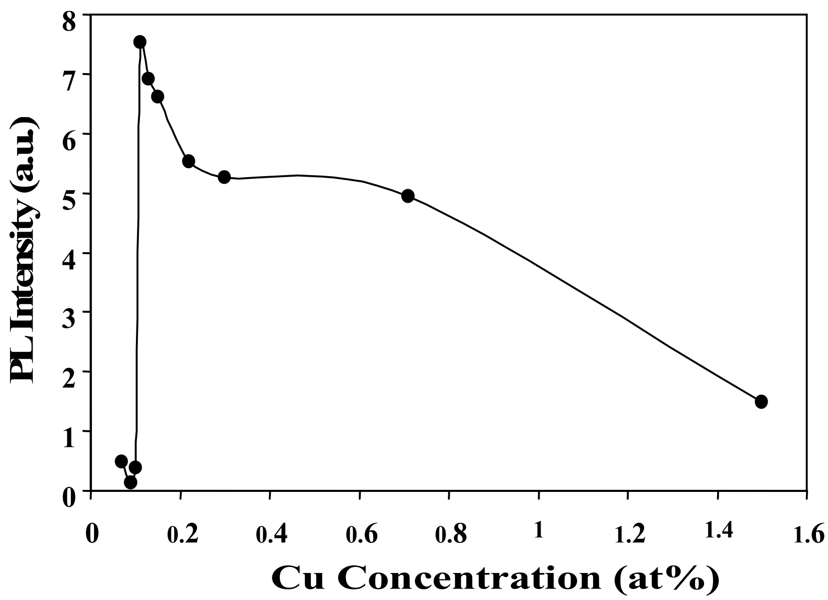

Figure 7. SrS:Cu Luminescent Brightness as a Function of Cu Concentration

Growth temperature uniformity and controllability is also important to the device performance since the growth rate of SrS is extremely sensitive to the growth temperature. More than 5% deviation can occur for a three-degree change in the growth temperature. The growth rate variation will also cause the deviation of Cu concentration since the Cu flux is kept constant. Sometime a 20% of variation of EL brightness was observed for this 5% growth rate change. It is also known that the mounting of substrates on the holder can contribute to varying substrate surface temperature due to the changing thermal contact between substrates and holder. Therefore, a real time surface temperature monitoring capability is also necessary for a repeatable SrS:Cu mass production. In terms of Cu flux control, we expect it to be a second order effect on the device stability. Copper has a very low vapor pressure and only a very small amount of Cu is used during the growth, therefore, the flux is very stable for a long period of time.

It is clear that the growth process of SrS:Cu poses many challenges because of the demanding conditions under which these materials have to be grown. Optimum device performance and high production yield require accurate composition control better than 1%. Several aspects of the fabrication process must be carefully monitored and controlled. To fully address this issue, the following are two suggested instruments that used together would offer simultaneous, precise vapor flux and temperature monitoring and control. We believe these control and monitoring instruments will be essential in providing high yield in production tools implemented for the manufacturing of AMEL displays.

2.3 Vapor Flux Monitor and Control

For vapor flux monitor and control, we propose to use Atomic Absorption Spectroscopy (AA). AA is a non-intrusive optical, highly sensitive and selective technique for determining the concentrations of atoms in the vapor phase. A light beam corresponding to the absorption line of the atomic species of interest is directed across the deposition chamber in front of the substrate where a portion of the beam is absorbed by the atomic flux. The exiting beam is detected and the absorption coefficient is used to compute the flux (see Figure 8). The instrumentation is located outside of the vacuum chamber thus fully compatible with standard thin film deposition environment. This non-intrusive system can be extended to simultaneously monitor fluxes of several different atomic species by exchanging the single-element lamp with a multi-element lamp or by an arrangement of multiple lamps specific to the materials in use such as Cu for SrS:Cu, and Zn and Mn for ZnS:Mn layer.

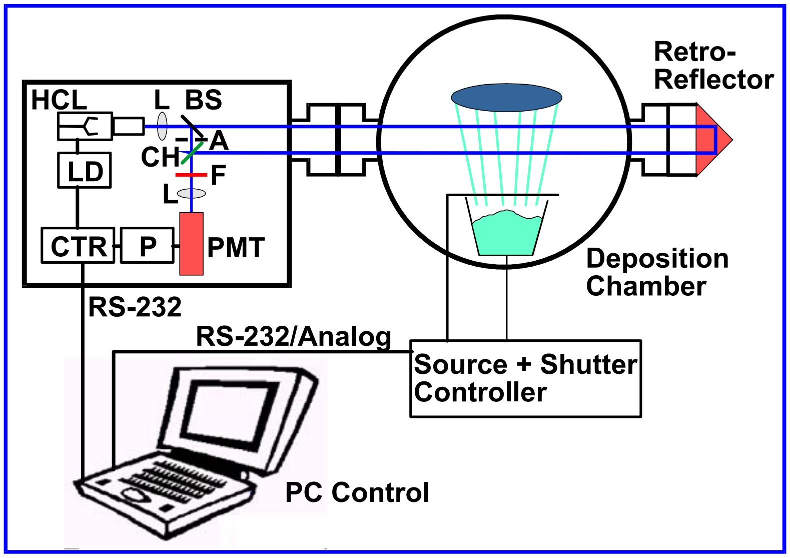

Figure 8. **Atomic Absorption Measurement Monitoring Technique, HCL= element specific lamp, L=lens, BS=beam splitter, A=aperture, CH=chopper, F=filter, PMT=detector, P=lock-in amplifier , LD=pulsed light source drive**

2.4 Substrate Temperature Monitoring and Control

An advanced temperature measurement system can be used specifically for MBE. It provides two-color pyrometry and two channels of narrow band reflectometry in a single instrument. The schematics of this instrument are shown in Figure 9. The unique feature of this monitoring system is its ability to simultaneously measure both the substrate temperature and the film growth rate. A major complication of accurate temperature measurement during deposition occurs when the deposited film has a different optical index of refraction from the substrate. During thin film deposition optical interference will occur between the interface and the surface and the pyrometric radiation from the substrate will alternately be enhanced and suppressed as the film becomes thicker. The instrument performs 950 nm reflectance measurements simultaneous with 950 nm pyrometry and uses the reflectance to compensate for the “varying emissivity” of the thin film stack and produce an accurate temperature reading.

This technique also provides real-time growth rate information. During film growth, the optical reflectance is monitored at 470 nm and 952 nm wavelengths. The period of oscillation, P, is proportional to the film index of refraction, n, and the growth rate, G, by the expression:

$$P = (2nG)/\lambda$$

Since the measurement wavelength, λ, is known, the product of n and G is found from fitting the oscillations to a theoretical model.

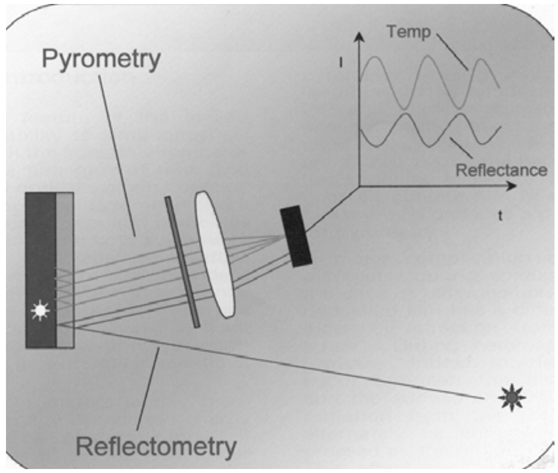

Figure 9. Reflectometry Enhanced Pyrometry

2.5 Summary of VPD SrS:Cu Process

A full process of MBE growth of SrS:Cu for AMEL displays has been developed. The SrS:Cu grown with this process should provide a high quality blue phosphor for AMEL application.

Growth materials:	Industrial grad H_2S, 99.9% pure distilled dendritic piece strontium
Doping material:	99.999% pure Cu wire 2.0mm diameter
Substrate mounting:	Mechanical
Temperature sensor:	Thermocouple
Growth temperature:	400°C
Flux sensor:	Ion gauge
Sulfur flow control:	1459C HPS flow controller, with 50 sccm full scale for N_2
Sulfur flow rate:	15% full scale during growth
Strontium flux control:	Thermal evaporation
Strontium flux:	5-6×10^{-6} torr
Copper flux control:	Thermal evaporation
Copper flux:	2×10^{-8} torr

Growth procedure: Preheat the strontium and copper effusion cell to the temperatures to produce the required flux. Increase the growth temperature to 400°C. Open source shutters to start growth. Grow SrS:Cu for 90 min. Close source shutters and stop sulfur flow. Increase the substrate temperature to 650-680°C. Open sulfur shutter and start annealing. The sulfur flow should be 5-6% full scale. Close sulfur shutter and turn off flow controller at 20 min. Ramp the substrate temperature down to 600°C in 10 min. Ramp the substrate temperature from 600°C to 200°C in 15 min. Unload the sample from the growth chamber into the load-locker chamber and wait until it reaches room temperature before taking the sample out.

2.6 Production Tool

We worked with one of the primary MBE production tool vendors, VG semicon, to perform cost of ownership analysis of a production tool for SrS:Cu. The most economical tool appears to be their largest model, V150 plus, which can accommodate either seven each 6" wafers or three each 8" wafers. The base model only has one growth chamber. To increase throughput, we could add another chamber for post annealing. The cost of base model is $4.5 million. The cost for additional annealing chamber is roughly $0.5 million depending on final design. Table 1. shows the throughput and cost per wafer assuming no depreciation of the tool.

Table 1. Comparison of Production MBE Tools With and Without Separate Annealing Chamber for Throughput and Cost Analysis

Machine type	Cost	# wafer/ run	# wafers/ day	# wafers/ year	# QVGA display/ year	Cost per display
Standard V150 plus	$4.5 million	7 x 6"	80	25800	2,735,539	$1.65
		3 x 8"	34	10486	2,020,431	$2.23
V150 plus with separate annealing chamber	$5.0 million	7 x 6"	112	36520	3,872,167	$1.30
		3 x 8"	48	15080	2,905,678	$1.72

Assumption:
1. Device size: 0.6" x 0.4"
2. Normal growth time: 1.2 hour
3. Normal annealing time: 0.6 hour
4. Total per platen time: 1.8 hour
5. Average # platen per 8 hour shift: 4
6. 2 scheduled and 1 unscheduled "turn around" per year @ 10 days/ turn around
7. 1000 wafers/year for calibration and other wastes.

3. Device Reliability

During the course of the program, device reliability was our most challenging problem when we were trying to make displays on IC wafers. We have found several sources for device failures.

3.1 Metalization Failure

Film cracking problem was first observed on IC wafers in Q4 (Figure 10). To identify the layer in the stack that is responsible for delamination, we subjected a wafer to the same heating cycles as used for growing SrS:Cu but without actual deposition. Microscope inspection revealed film delamination in the contact pad area showing adhesion between IML2 and M2 to be weak. Since patterned test wafers having Ti-W metallization did not exhibit any film cracking problem, we concluded that film cracking only occurred on wafers having CVD-W metallization. After switching to IC wafers with Ti-W metallization, we no longer encountered any film cracking problem (Figure 11). It appears that film cracking problem is caused by the poor adhesion between CVD-W and inter-metal dielectrics, a process problem in IC foundry.

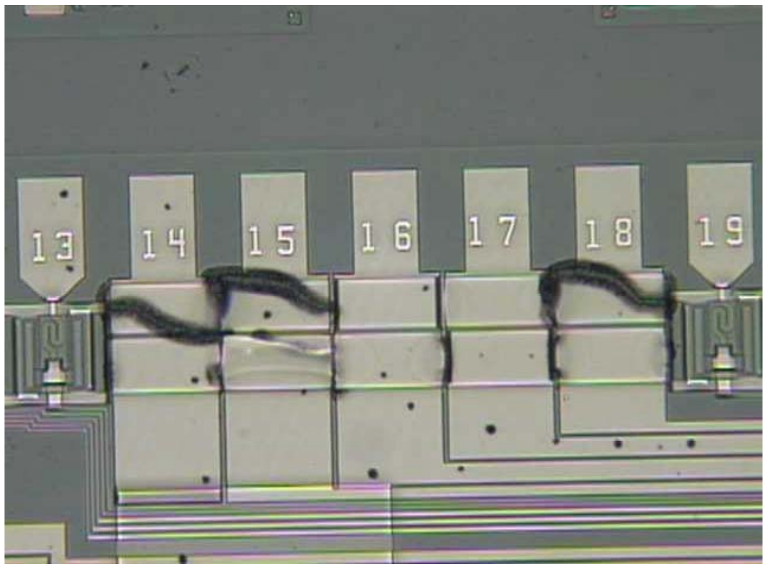

Figure 10. Film Cracking on IC Wafers with CVD-W Metalization

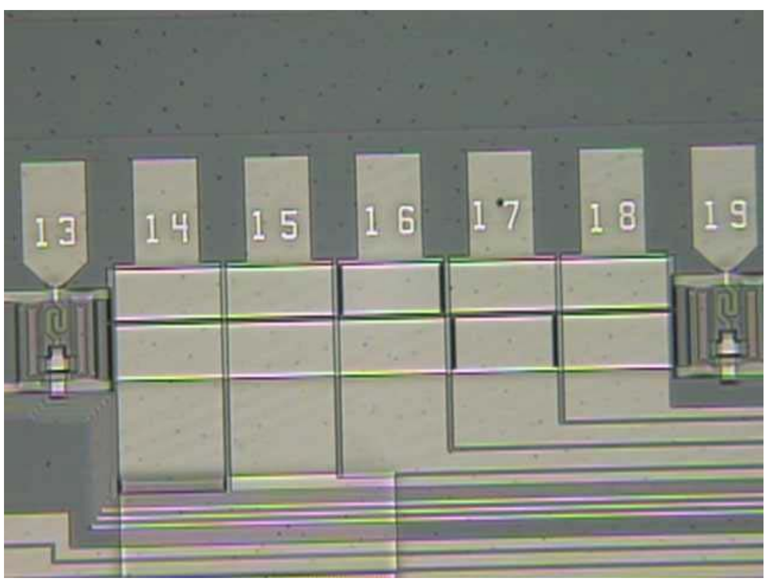

Figure 11. No Film Cracking Was Observed on IC Wafers with Ti-W Metalization

3.2 Annealing defects

Optical microscopy studies showed that these instabilities occurred in samples exhibiting a large density of measles-like defects, seen as black spots in Figure 12 (a). This defect was observed to be related to slight perturbations in the normal VPD SrS:Cu process. A close correlation between the defect density and the sulfur anneal conditions was found to exist, but only when an excess Cu concentration existed during the growth and only on AMEL IC wafers. Consequently, these defects were related to the premature reaction of S with Cu on the AMEL substrate surface, before the onset of large grain growth during the annealing. Based on this understanding, a series of annealing studies with controlled sulfur injection and substrate temperatures were carried out for the purpose of eliminating the measles defects.

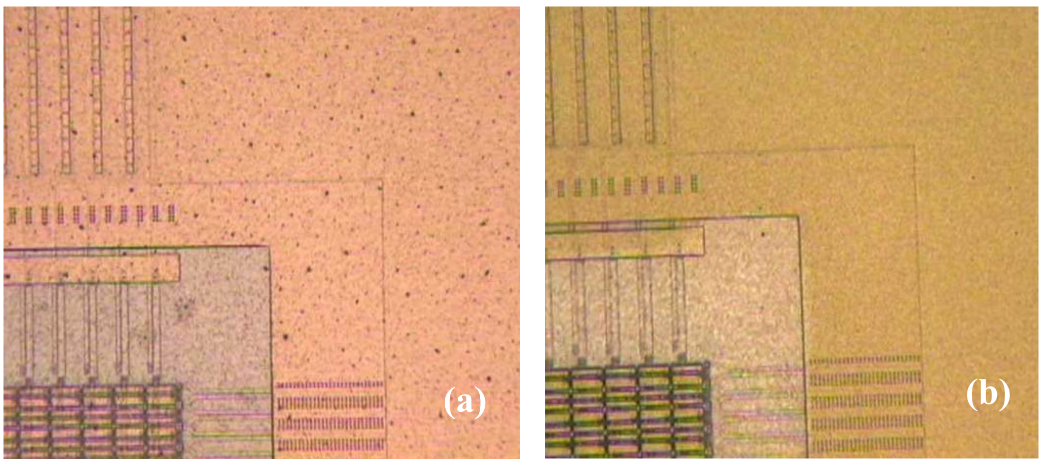

Figure 12. SEM Pictures of ZnS:Mn/SrS:Cu/AMEL Devices: (a) a high density of measles defects was observed with the standard *in-situ* sulfur anneal process (b) no measles defects and a much higher device performance in terms of both EL brightness and reliability with the pulsed sulfur anneal process.

A controlled sulfur *in-situ* post anneal was found to not only greatly reduce the dark spot density, but also to improve device performance. Two controlled sulfur anneal techniques were developed to reduce the measles defects. The first one used a reduced anneal sulfur flow rate, e.g., 5% (standard rate: 7.5%), and sulfur flow was only turned on when the substrate temperature reaches target anneal temperature of 650°C. The second method was a new pulsed sulfur flow annealing technique, i.e., sulfur flow was only turned on for a very short period of time during annealing. We have learned from previous studies that SrS:Cu recrystallized in a relatively short time (less than 2 minutes) during the anneal. It is possible, therefore, only to introduce the sulfur at the grain growth phase and thus to totally eliminate the premature reaction by cutting off the sulfur flow when the grain growth is completed. By rigorous control of the sulfur flow rate during the anneal cycle to eliminating excess accumulation of Cu on the substrate surface, both techniques effectively reduce the chance of premature reaction between sulfur and Cu and consequently reduce the defect density and achieve much improved device reliability and luminance performance. Figure 12 (b) shows the surface images of samples annealed at standard condition and reduced sulfur exposure condition. With a reduced sulfur anneal, device reliability was greatly improved and we were able to produce fully functional and reliable white monochromic AMEL displays

4. Display Fabrication and Characterization

The AMEL display demonstrator we have chosen for this program has a quarter video graphics array (QVGA) format, i.e., 320 x 240. To handle 1.4" square wafer pieces, we have to set up a separate process line since our AMEL production line tools are designed to process 6" round wafers. We used an old Tamarak exposure station fitted with a custom made micropositioner stage to manually align the substrates with photomask. An old resist spinner was used for resist application and developing was done in beakers. The largest yield hit (after phosphor reliability) was the yield of metal 4 process. The integrity of metal 4 process is critical for yielding dies with functional circuits. The common problems are the shorts between conductor lines and incomplete coverage of vias due to misalignment, incomplete resist exposure/development or over etching. By learning the limitation of manual lithography operation and developing countermeasures, e.g., repeating lithography steps, we were able to improve the die circuit yield from 25 % in Q5 to $\geq$60 % toward the end of the program as shown in Figure 13.

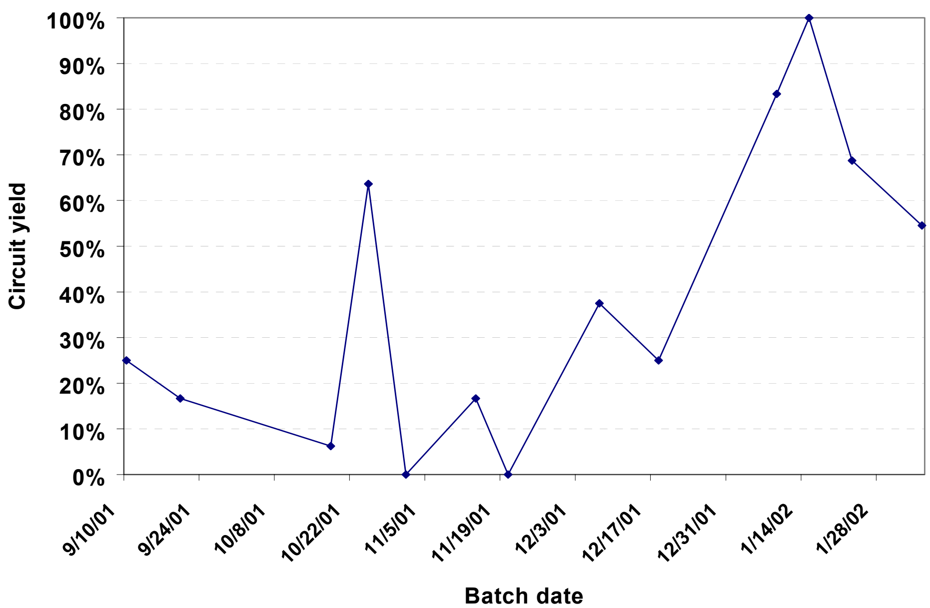

Figure 13. Circuit Yield of AMEL Dies vs. Batch Completion Dates

With both circuit yield increase and phosphor reliability improvement, we have successfully produced three SrS:Cu-based white monochrome QVGA AMEL displays. One operating with a video image is shown in Figure 14. It has very good brightness (> 90 fL) and gray scale. These operational AMEL displays have been aged for three hours and are expected to be reliable demonstration displays. We would have hoped for better yield of functional displays. However, considering the known sources for yield loss presented in our processing particle and chemical contamination of insulator and phosphor layer due to extra handling and moisture exposure, we believe this is still a fairly good yield.

Color luminance performance of SrS:Cu based white AMEL was measured by laying color filter plates over a full frame white image and the results are shown in Table 2 (The devices were driven with video signal using ET-1 electronics). A SrS:Ce based white monochrome AMEL was also measured for comparison. As shown in Table 1, the luminance performance improvement achieved by replacing SrS:Ce with SrS:Cu matches what we have observed on dot devices (see Q4 progress report). The color of blue filtered SrS:Cu based devices is a true blue with CIE (x, y)= (0.127, 0.128), a significant improvement over the cyan color measured from SrS:Ce based devices, CIE (x, y)= (0.099, 0.298). This represents nearly a factor of six increase in luminance when the color, e.g., CIE y, is normalized (Figure 15). In addition, the filtered green brightness in SrS:Cu based devices is still as strong as SrS:Ce devices despite the fact that the emission around 530 nm is expected to be weaker in the former device.

Figure 14. A Functional SrS:Cu-based White Monochrome QVGA AMEL showing a Video Image.

Devices	Color filter	V_{th}/V_{mea}	L (fL)	CIE x	CIE y
SrS:**Cu**/ZnS:Mn	None	120 V/160 V	205.0	0.372	0.377
	Blue		**16**	**0.127**	**0.128**
	Red		33.4	0.625	0.358
	Green		81	0.361	0.553
SrS:**Ce**/ZnS:Mn	None	136 V/170 V	131.0	0.438	0.479
	Blue		**7.0**	**0.099**	**0.298**
	Red		21.0	0.630	0.363
	Green		54.0	0.369	0.584

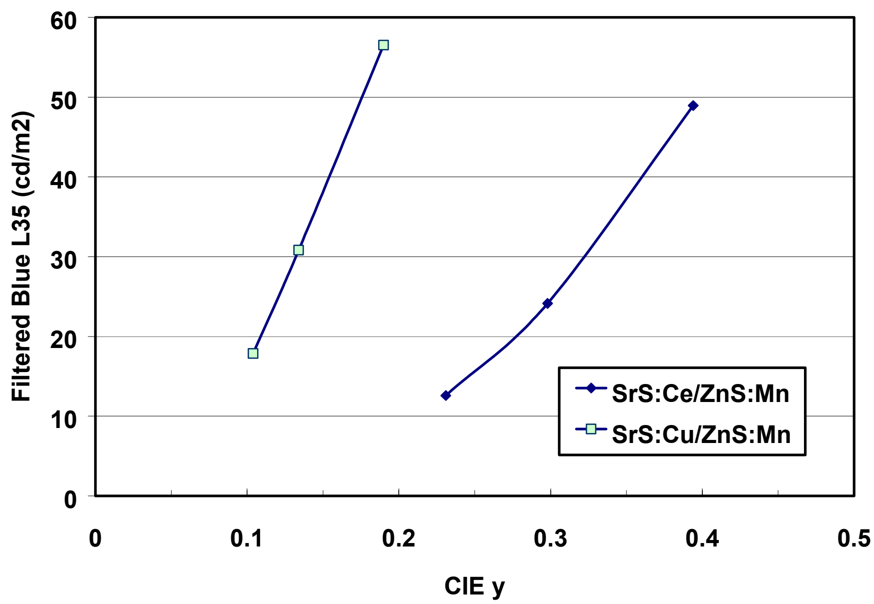

Figure 15. Filtered Blue Brightness of SrS:Cu and SrS:Ce-based White Phosphor

5. Conclusions

We have successfully developed a vapor phase deposition (VPD) process for SrS:Cu for the fabrication of active matrix EL displays on Si wafers. Processing issues such as substrate effect and sulfur annealing were carefully investigated. A clear understanding of these issues allowed us to optimize process conditions to achieve high reliability and luminance on real IC wafers.

A new process infrastructure was established to perform post deposition photolithography on 1.4 inch square substrates for the fabrication of AMEL displays. We were able to steadily improve the circuit yield and produced several functional and reliable displays toward the end of the program. These SrS:Cu-based white monochrome AMEL displays performed as expected and exhibited a factor of six increase in blue luminance over SrS:Ce-based white monochrome displays.

In summary, we have successfully met the objective set for this program, i.e., to develop a manufacturable SrS:Cu blue phosphor process for the production of white monochrome and full color AMEL displays, by demonstrating functional SrS:Cu-based white monochrome QVGA displays with blue and white luminance performance greatly exceeds the SrS:Ce-based displays currently in production. We also have investigated and identified necessary tools for manufacturing SrS:Cu-based full color AMEL with high yield. All these efforts form the basis for producing cost effective and high performance full color AMEL displays for military and civilian applications which is the ultimate goal of this government program.

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